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Characterizing Lasers that Emit Widely Diverging Radiation

by Richard L. Tober

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14. ABSTRACT

It is often difficult to accurately measure the power emitted from mid- and long-wave IR lasers because their inherently large radiation divergence. This is simply due to the fact that experimental geometry limits the solid angle of the emitted radiation that the sensitive area of a power meter can capture. However, one can confidently estimate the total power emerging from a widely diverging laser by integrating the power of an elliptically symmetric Gaussian beam that is incident on the meter's sensitive surface

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Introduction

Electrically pumped quantum cascade lasers (QC lasers) and interband cascade lasers (IC lasers) are currently being developed for a wide variety of commercial and defense applications (*1 through 6*). Of course, rapid development requires precise characterization so that feedback can be provided for improving not only laser designs but growth techniques as well.

Characterizing cascade laser device current and bias parameters is fairly straightforward. However, power measurements are often difficult as their emitted radiation is widely diverging. The large divergence is due to QC and IC laser emission wavelengths and structure geometry (*7,8*). The situation is further exacerbated by mechanical isolation if the laser needs to be operated at low temperatures.

Figure 1 shows a schematic of the experimental apparatus. The QC laser is mounted on the cold finger of a cryostat in such a way that it is separated from the power meter's sensitive area by 20 mm. The meter can only capture laser radiation within a solid angle of 50.8° The radiation from this laser has a fast axis ($1/e^2$) divergence of 106° and a slow axis ($1/e^2$) divergence of 57°. Thus, the sensitive area of the power meter captures only a fraction of the emitted radiation.

This report documents the results of laser experiments and theoretical calculations performed to determine a method to characterize the specific operating parameters of widely diverging lasers. Specifically, it shows how the total power emerging from a widely diverging laser can be confidently determined.

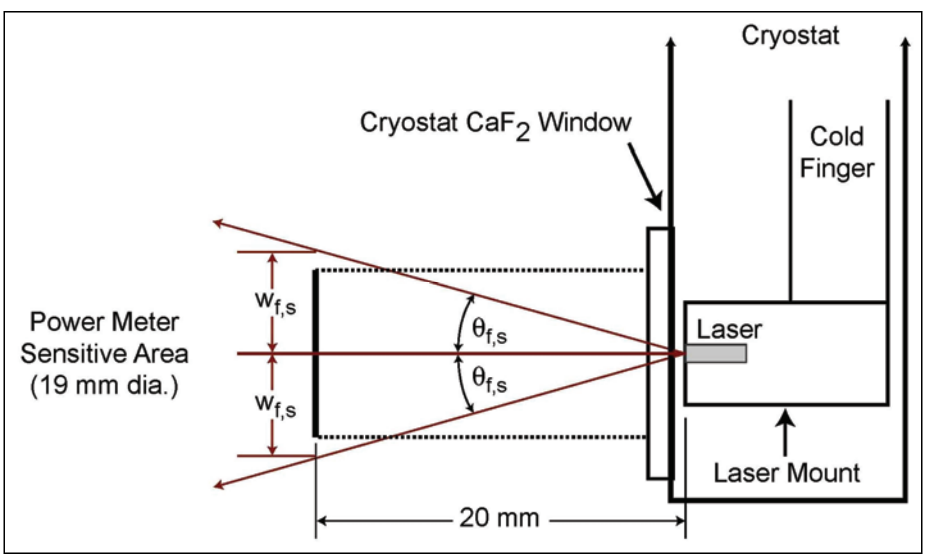

Figure 1. Schematic of experimental apparatus. The sample was separated from the power meter's sensitive area by 20 mm. The meter captured radiation in a solid angle of 50.8°.

Experimental

A quantum cascade laser (QCL 07-562) was mounted in a Janis ST-100 cryostat so that it could be maintained at 288 K. Power was applied to the laser using an Avtech current pulser, the peak current and peak bias were measured using a LeCroy digital oscilloscope, and the power was measured using a Molectron power meter. Spectra were acquired using a McPherson 2/3 meter monochromator. All results and measurement parameters are listed in table 1 and data are shown in figures 2 through 5.

Table 1. QCL 07-562 operating characteristics @ 288 K.

Operating Characteristic	**Symbol**	**Value**	**Unit**	**Comments**
Temperature	T_{op}	288± 1	K	Heat Sink Temperature
Threshold Current	I_{th}	0.96 ± 2%	Amps (peak)	500 nsec pulses 10 kHz rep. rate
Maximum (tested) Operating Current	I_{max}	2.33 ±2%	Amps	500 nsec pulses 10 kHz rep. rate
Maximum (tested) Operating Voltage	V_{max}	13.42 ±2%	Volts	500 nsec pulses 10 kHz rep. rate
Maximum 2-Facet Output Power	P_{2-f}	664 ±3%	mW	2- facet peak power, T_{op} = 288 K, V_{op} = 12.44 V and I_{op} = 1.83 Amps
Slope Efficiency	η	1.2 ±4%	W/A	$I > I_{th}$, $\delta P_{2-f}/\delta I$
Central Wavelength	λ_{cent}	5.83 ±0.02	µm	**V** = 11.83, I = 1.54 Amps
Fast Axis Divergence	θ_f	106°	degrees	$1/e^2$
Slow Axis Divergence	θ_s	57°	degrees	$1/e^2$

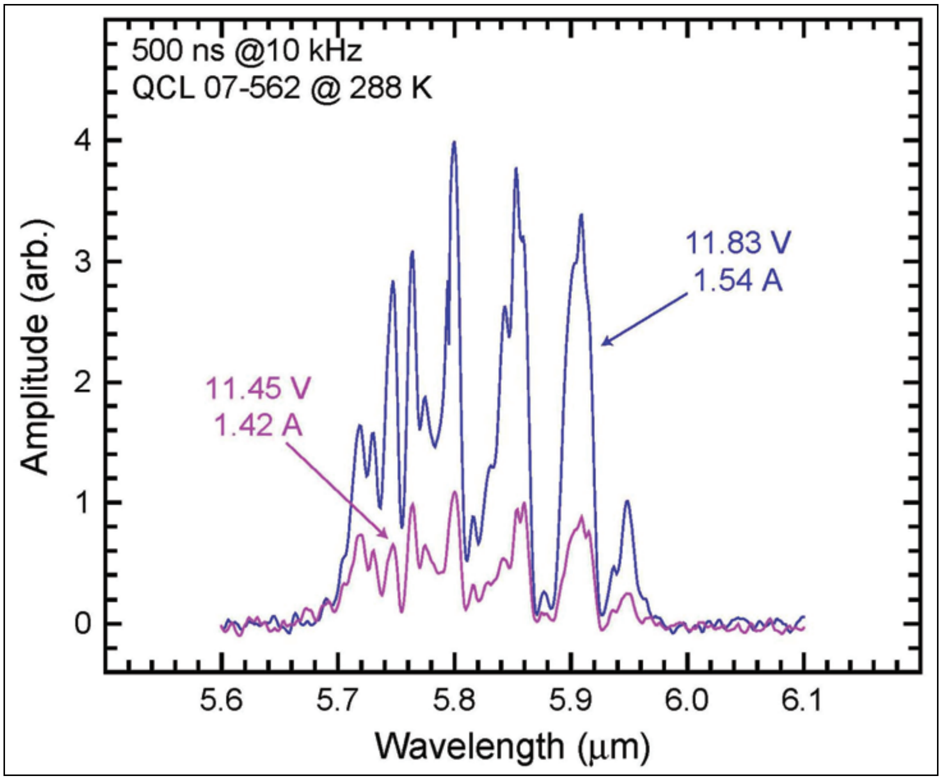

Figure 2. Spectra obtained from the sample QCL 07-562 at 288 K and 2 different bias values.

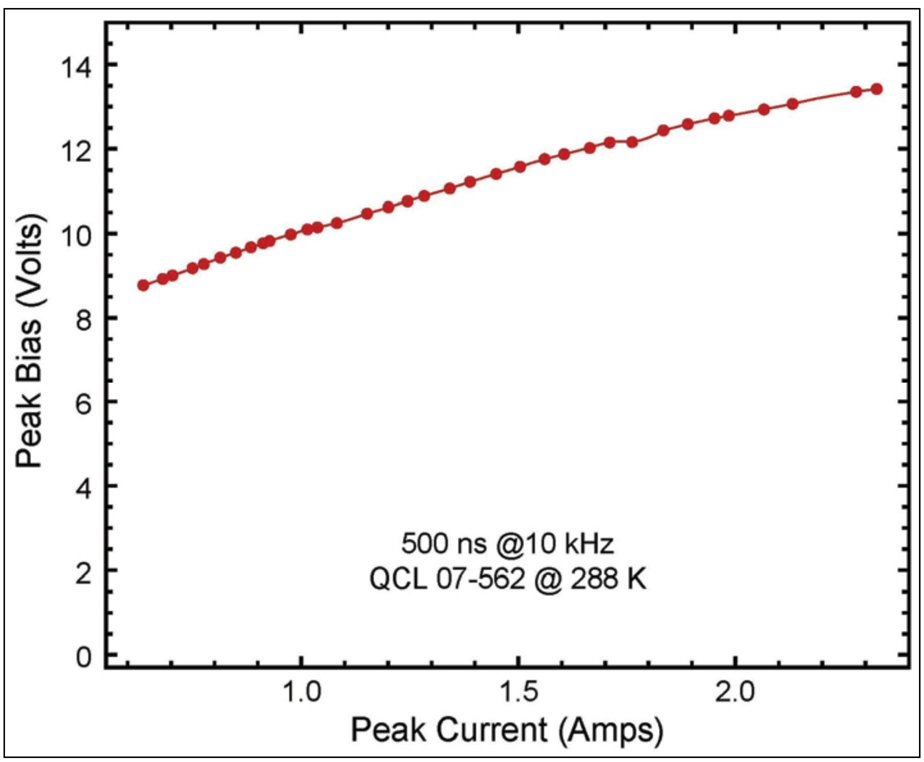

Figure 3. Peak bias versus peak current.

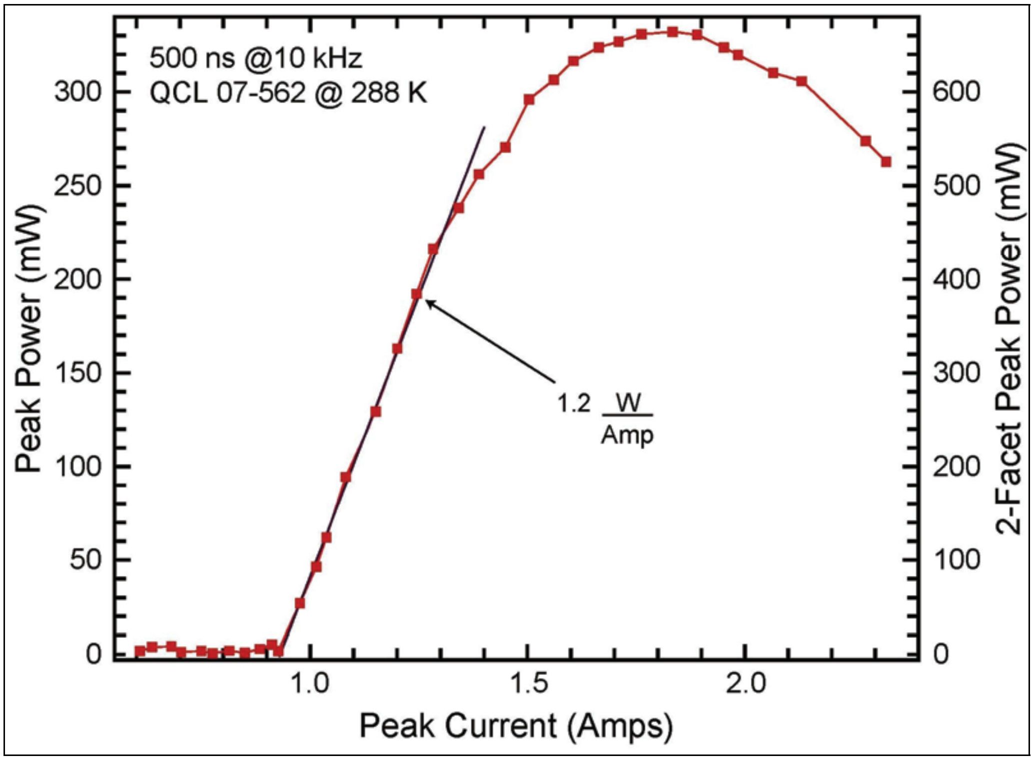

Figure 4. Peak power versus peak current.

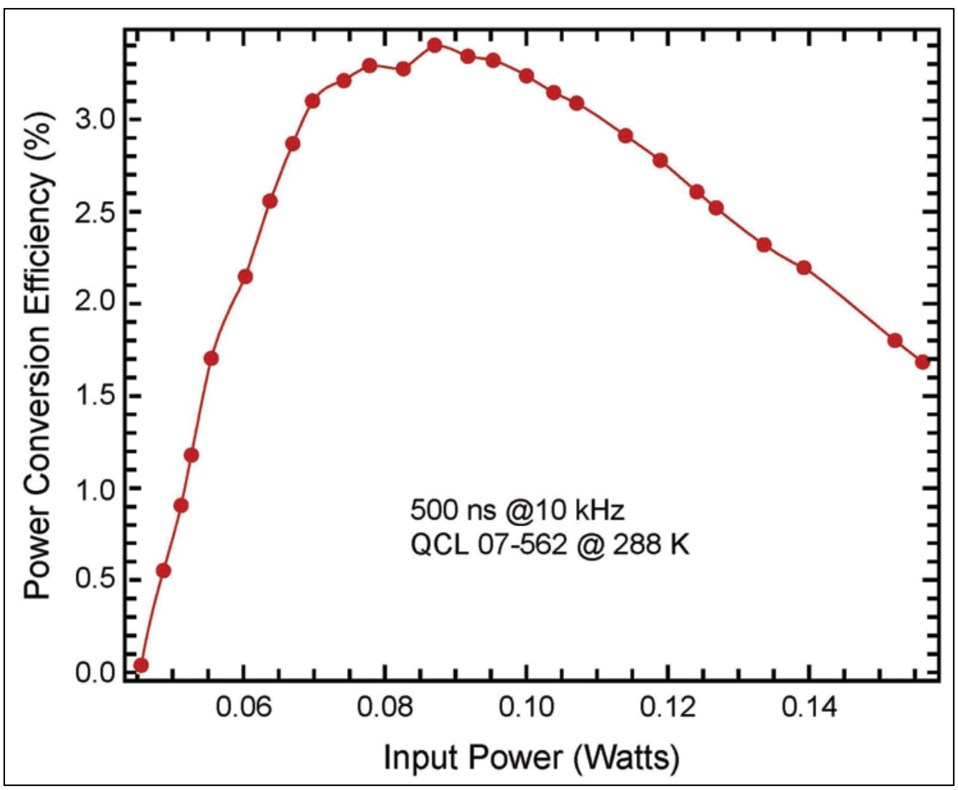

Figure 5. Power conversion efficiency versus input power.

This QC laser was operated in an evacuated cryostat and was, therefore, separated from the power meter's sensitive area by a CaF_2 window and a distance of 20 mm.

First, spectra were obtained in the spectral range between 5.6 and 6.1 μm using 500 ns pulses at 10 kHz, and at 1.42 and 1.54 amps (peak). The emission had multiple longitudinal modes at both currents commensurate with the 3 mm long mesa waveguide (see figure 2). The radiation over filled the collection optics, but posed no problem for determining the emission spectra.

Next, a bias was applied to the sample so that power, current, and voltages could be simultaneously measured. Figure 3 shows the voltage across the mesa as a function of the applied current. Similarly, figure 4 has power plotted as a function of the applied current. The raw power data was adjusted for the 92% window transmission and multiplied by a power adjustment factor commensurate with the amount of radiation actually captured by the power meter (see figure 1 and the analysis described below). Note that the vertical axes indicated the peak power as measured and the peak power as if equal amounts exited both facets (the facets were uncoated).

A portion of the data, just above threshold, was fit to a straight line. The slope yielded the internal quantum efficiency (1.2 W/Amp), the x-axis intercept indicated the 0.96 Amp threshold current (both values are listed in table 1). The slope of the power versus current curve decreased after about 1.4 amps and became negative at 1.56 Amps. This reduction in slope was due to the decreasing efficiency that accompanied the current induced temperature increases.

The power conversion efficiency (*PCE*, see figure 5) was calculated by assuming equal amounts of radiation was emitted from each facet, then dividing twice power (as measured with the power meter) by the average current-voltage product.

$$PCE = \frac{2 \times P_{meas}}{(I \times V)_{ave}}$$

Analysis

Since the power meter had a limited field of view, a power adjustment factor (PAF) was used to adjust the measured data to a value commensurate with the total laser power emitted. The PAF was calculated as a ratio of the total power contained in an elliptically symmetric Gaussian to that captured by the surface area of the power meter.

The procedure follows from the fact that the power contained in a Gaussian beam can be determined as follows:

$$P_{Total} = \int I_{x,y} dA = I_0 \int_{-\infty}^{+\infty} e^{\frac{-2x}{w_x}} dx \int_{-\infty}^{+\infty} e^{\frac{-2y}{w_y}} dy \qquad (1)$$

where I_0 is the beam intensity, $I_{x,y}$ is the Gaussian intensity profile; dA is the cross section of the laser beam at the position of the power meter's sensitive surface; w_x and w_y are the beam waists in the x and y-directions, respectively; $w_{x,y} = z \tan \theta_{f,s}$ where $\theta_{f,s}$ are the $1/e^2$ half angle beam divergences for the fast and slow axes; z is the position of the power meter; and the limits of integration extend to infinity.

The total power captured by the power meter can be calculated using:

$$P_{meas} = I_0 \int_{0}^{r_{x,y}} e^{\frac{-2x}{w_x}} dx \int_{0}^{r_{x,y}} e^{\frac{-2y}{w_y}} dy \qquad (2)$$

where the limits of integration now extend only over the surface area of the power meter's sensitive area. Equation 2 must be integrated numerically in its present form. However, if you approximate the power meter's circular surface with a square having the same area ($4s^2 = \pi r^2$) then the integral can be readily evaluated using error functions. The PAF can then be written as:

$$PAF = \frac{P_{Total}}{P_{meas}} = \frac{\int_{-\infty}^{+\infty} e^{\frac{-2x}{w_x}} dx \int_{-\infty}^{+\infty} e^{\frac{-2y}{w_y}} dy}{\int_{-s}^{+s} e^{\frac{-2x}{w_x}} dx \int_{-s}^{+s} e^{\frac{-2y}{w_y}} dy} \qquad (3)$$

Results and Discussion

Table 1 shows performance details of the quantum cascade laser QCL 07-562. Experimental uncertainty and conditions have been included as well. Of note is the fact that the power determined as discussed above agrees, within in the experimental error, with values obtained using an integrating sphere capable of capturing all the emitted radiation (*9*). Further, additional independent studies (*10*) using well calibrated visible lasers have verified that the techniques described do provide a credible method for determining the total power emitted from widely diverging lasers.

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